Seeding and Self-seeding at New FEL Sources
ICTP, Adriatico Guesthouse / Trieste, Italy / 10-12 December 2012

Science driven requirements for seeded FEL

Challenging the Free Electron Lasers Photon Parameters and the Future Science

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and

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Cross-cutting Scientific Challenges Requiring Next-generation Light Sources

CONTROL OF COMPLEX MATERIALS AND CHEMICAL PROCESSES

REAL TIME EVOLUTION OF CHEMICAL REACTIONS, MOTION OF ELECTRONS AND SPIN

IMAGING AND SPECTROSCOPY OF INDIVIDUAL NANO-OBJECTS

STATISTICAL LAWS OF COMPLEX SYSTEMS

SIMULTANEOUS ULTRASHORT AND ULTRAFAST MEASUREMENTS

- Can we solve the problem of HTSC ?
- Can we understand the coexistence of SC and ferromagnetism?
- Can we make imaging resolution with an information content better than STEM of living matter ?
- Can we make material with a photovoltaic efficiency as in the natural process?
- How small and how fast can we make the magnetic recording devices?
- Can we observe a catalytic process under real operating conditions ?
- Can we fill the gap between the atomic and condensed matter properties ?
- How far can we push our capability to observe the matter under ultra-extreme conditions?

✓Brightness
✓Spectral brightness
✓**Temporal structure**
✓**Polarization,**
✓**Coherence,**
✓**Tunability,**
✓**Pulse Repetition Rate**

FTL

$$\Delta E \bullet \Delta t \geq \frac{\hbar}{2}$$

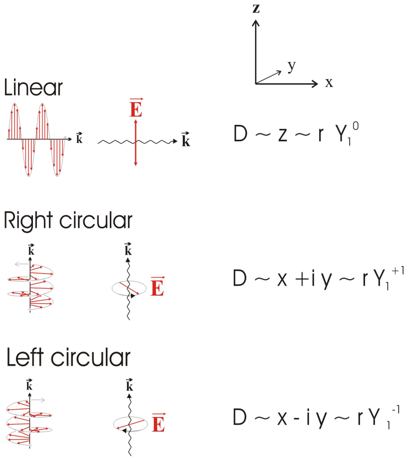
$$i\hbar\frac{\partial}{\partial t}\Psi = -\frac{\hbar^2}{2m}\nabla^2\Psi + V\Psi$$

$$X(\omega) = \int_{-\infty}^{\infty} x(t)\, e^{-i\omega t}\, dt$$

$$x(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} X(\omega)\, e^{i\omega t}\, d\omega,$$

Absorption Intensity ~ $|<f|\mathbf{D}|i>|^2$

$\mathbf{D} = \mathbf{E}\bullet\mathbf{r}$ is dipole operator



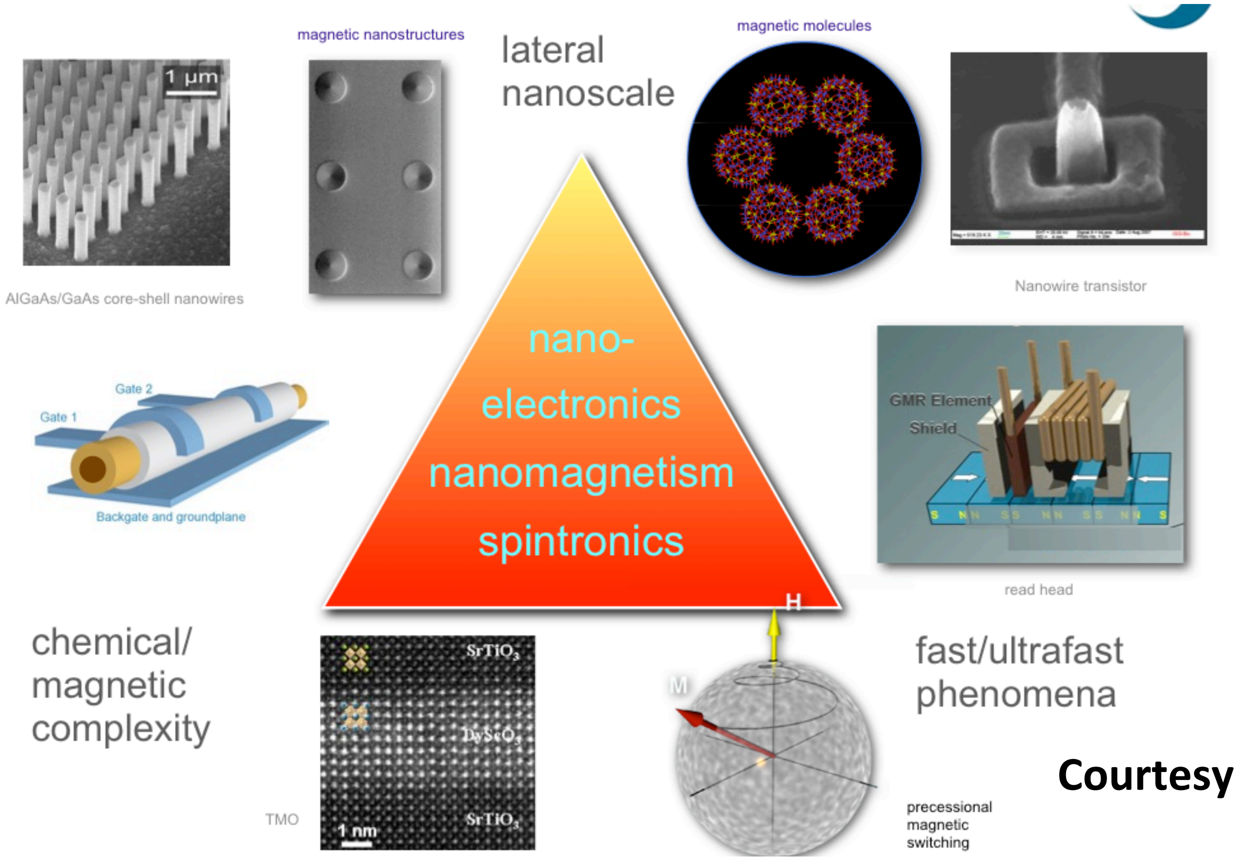
$D \sim z \sim r\ Y_1^0$

$D \sim x + i y \sim r\, Y_1^{+1}$

$D \sim x - i y \sim r\, Y_1^{-1}$

Selection rules:
$\Delta l = \pm 1,\ \Delta s = 0,\ \Delta j = 0, \pm 1$

EXPERIMENTS IN THE TIME DOMAIN
EXPERIMENTS IN THE ENERGY DOMAIN

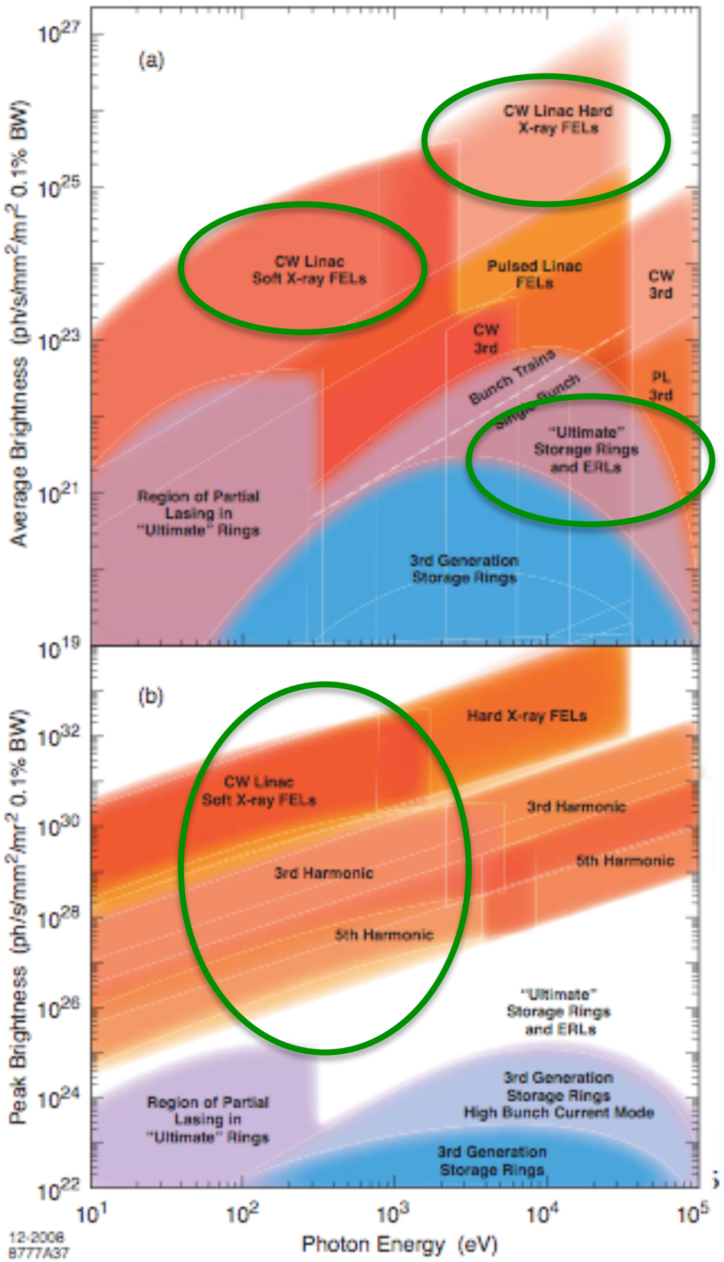


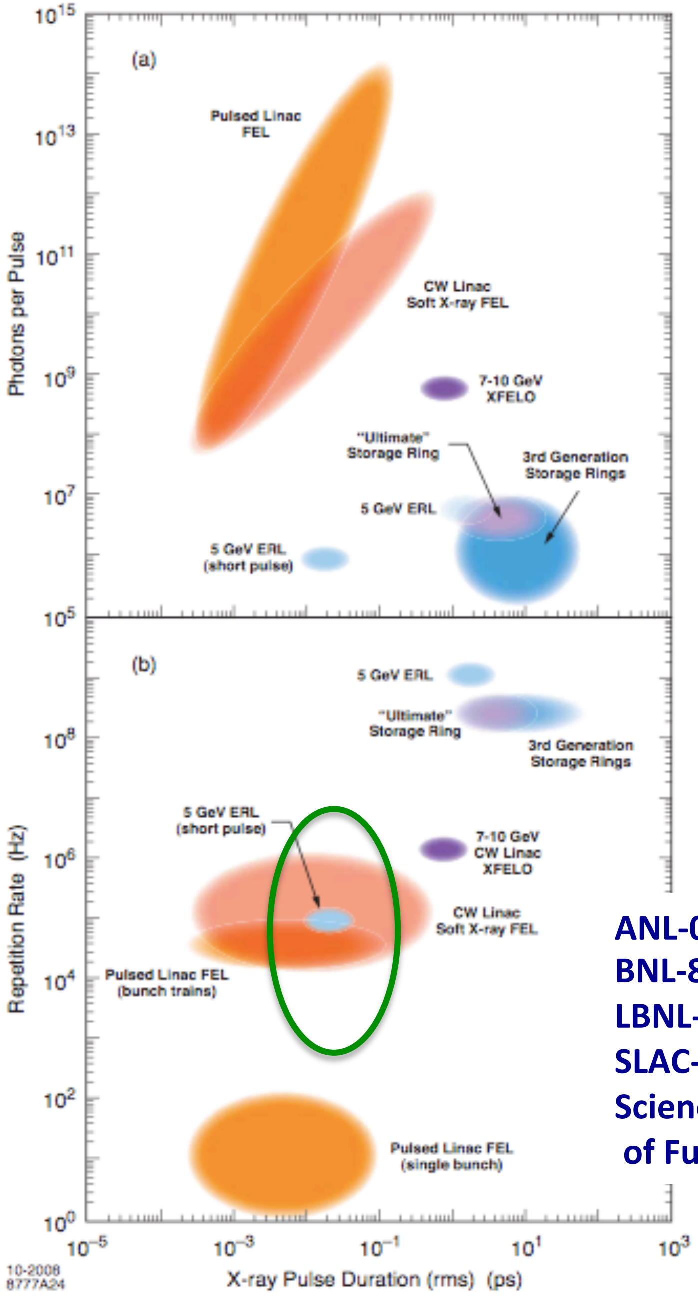
Courtesy C. M. Schneider

To set the path for probing the matter with the length, time and energy resolution required for exploring critical and exotic phenomena:

nm, fs (as), and sub-meV

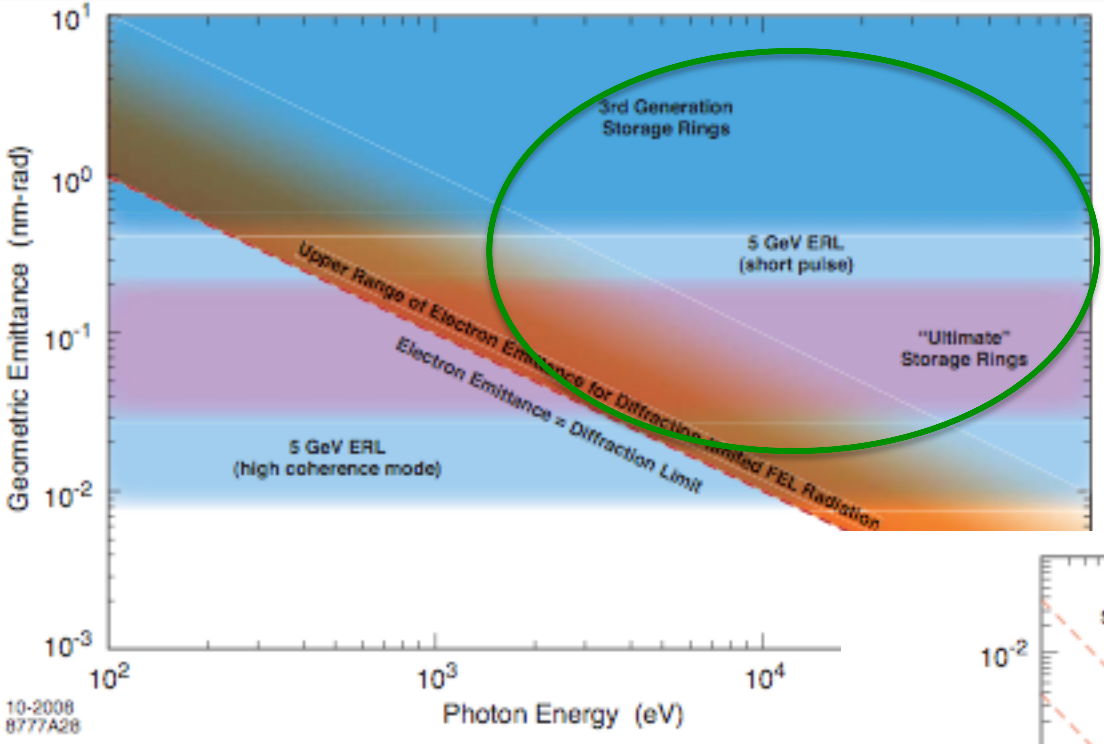
Future Light Sources

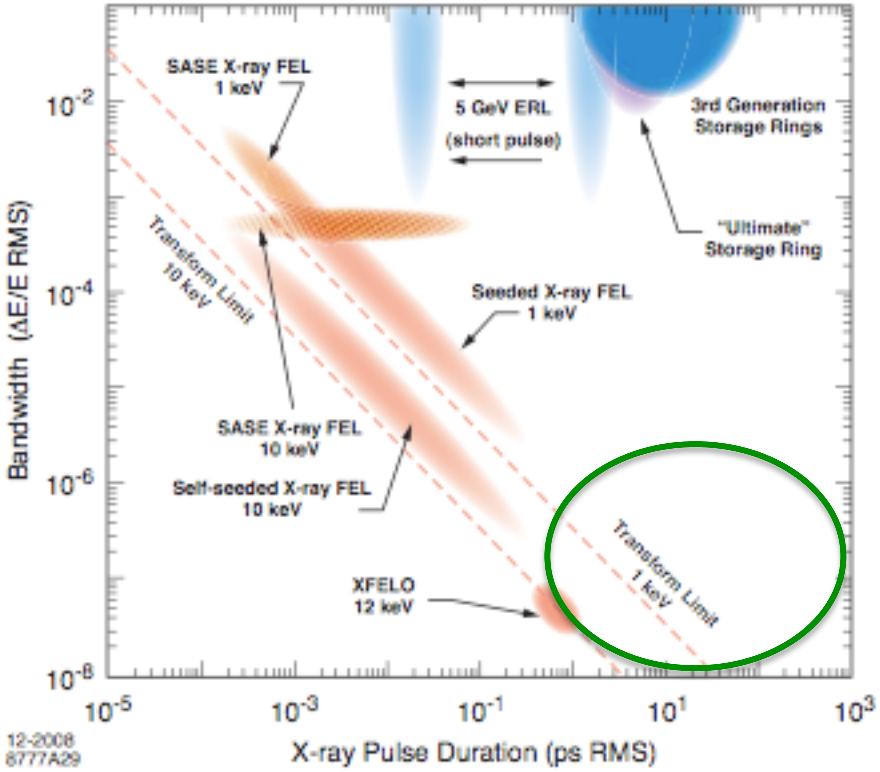




ANL-08/39
BNL-81895-2008
LBNL-1090E-2009
SLAC-R-917
Science and Technology
of Future Light Sources

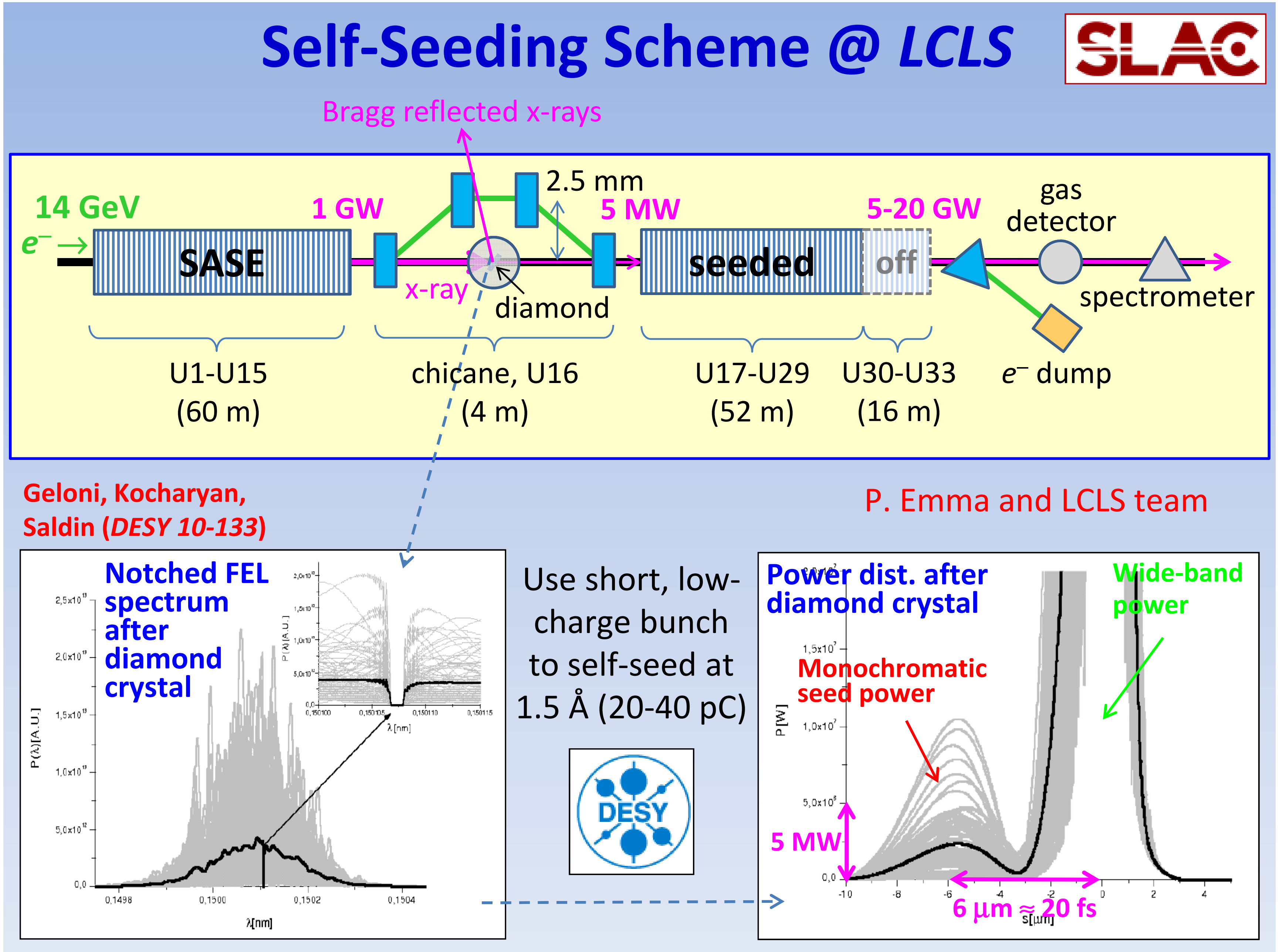
Future Light Sources





ANL-08/39
BNL-81895-2008
LBNL-1090E-2009
SLAC-R-917
Science and Technology of Future Light Sources

Self-seeding LCLS



Self-Seeding Scheme @ *LCLS*

Geloni, Kocharyan, Saldin (*DESY 10-133*)

P. Emma and LCLS team

Notched FEL spectrum after diamond crystal

Use short, low-charge bunch to self-seed at 1.5 Å (20-40 pC)

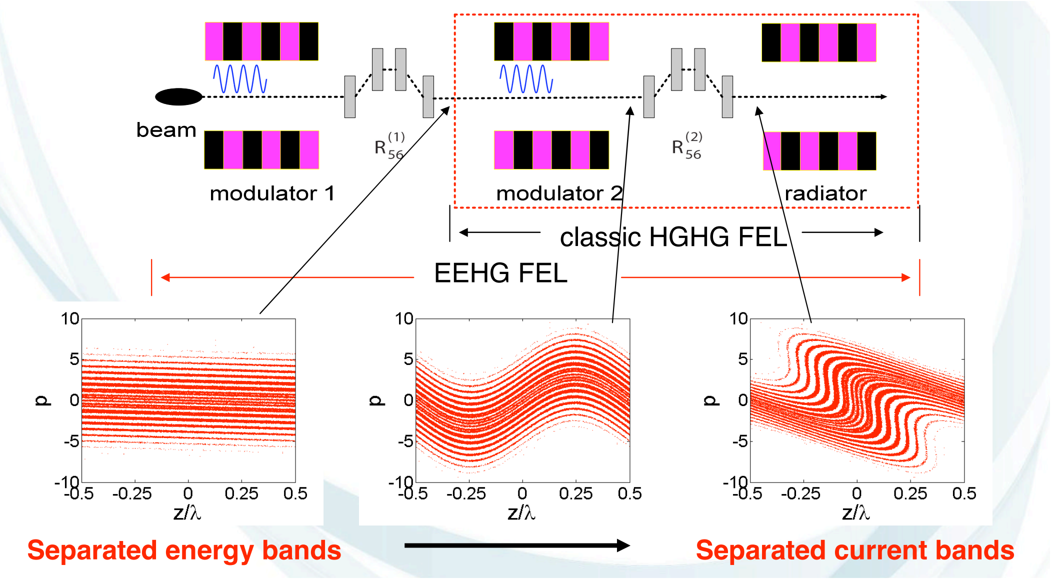
Power dist. after diamond crystal

Wide-band power

Monochromatic seed power

New FEL concepts FELs

ECHO schema, as generation, hard x-ray cavity

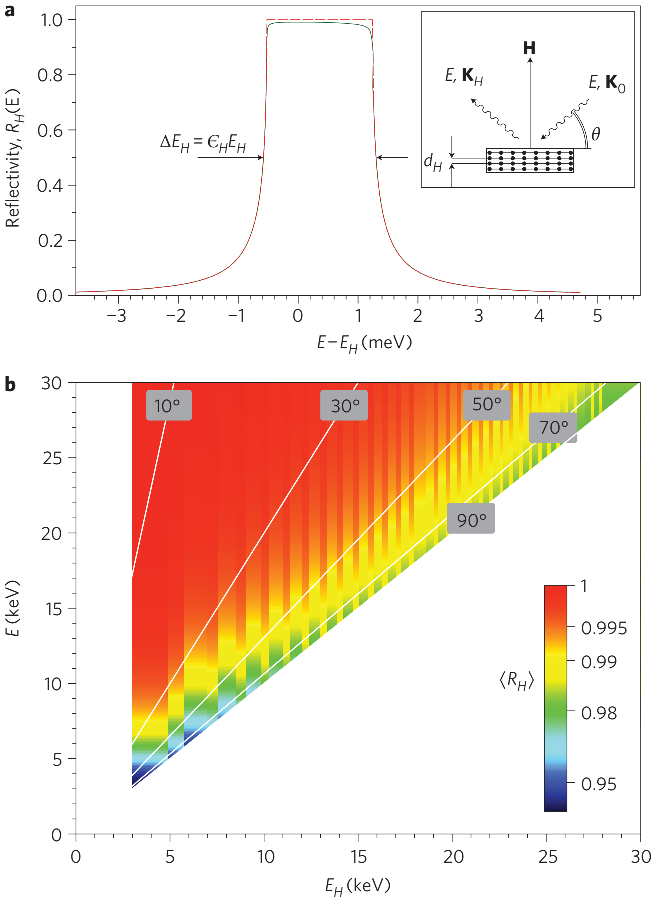


Dao Xiang, SLAC

[LCLS]

[SCSS: *SPring-8* Compact SASE]

Swiss-FEL



Near-100% Bragg reflectivity of X-rays
Yuri Shvyd'ko et al.

NATURE PHOTONICS 5 (2011)

FEL seeding modes and FERMI@Elettra

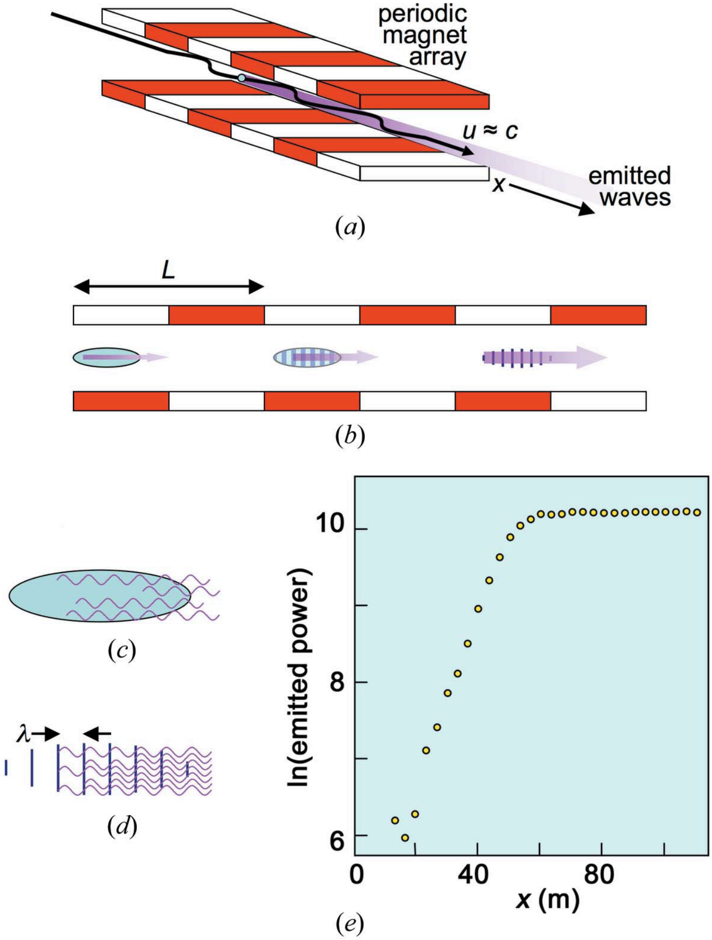
SASE

SEEDED

HGHG

HHG

NEW SCHEME



(*a*) (*b*) (*c*) (*d*) (*e*)

FERMI@Elettra team

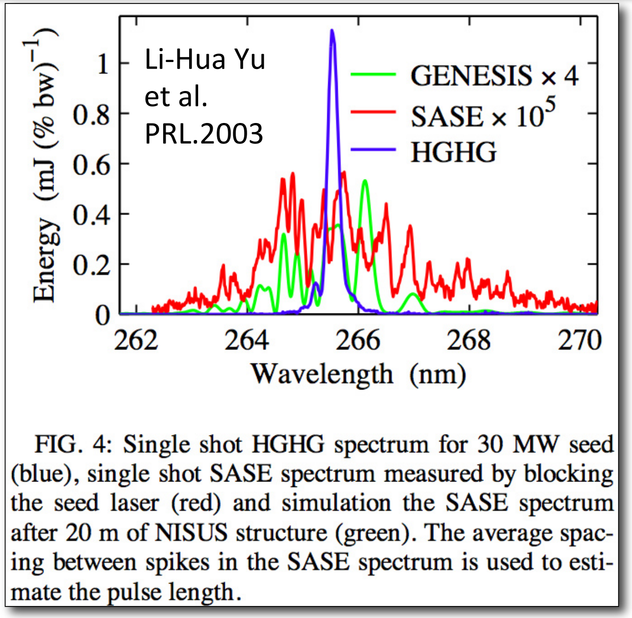
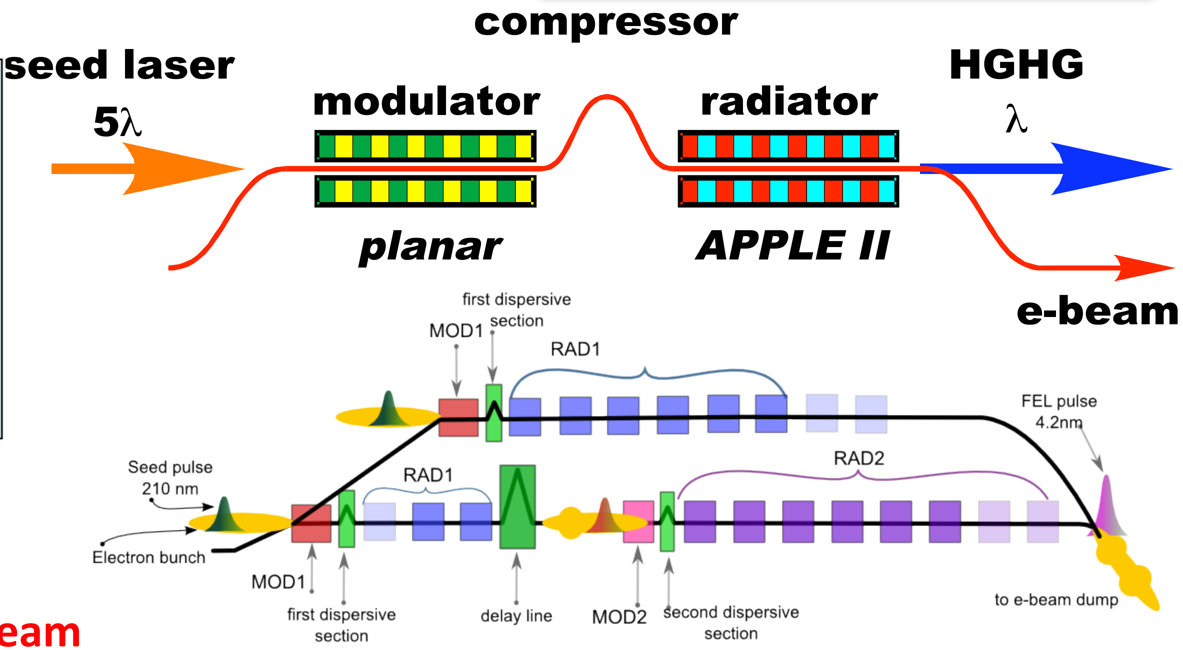


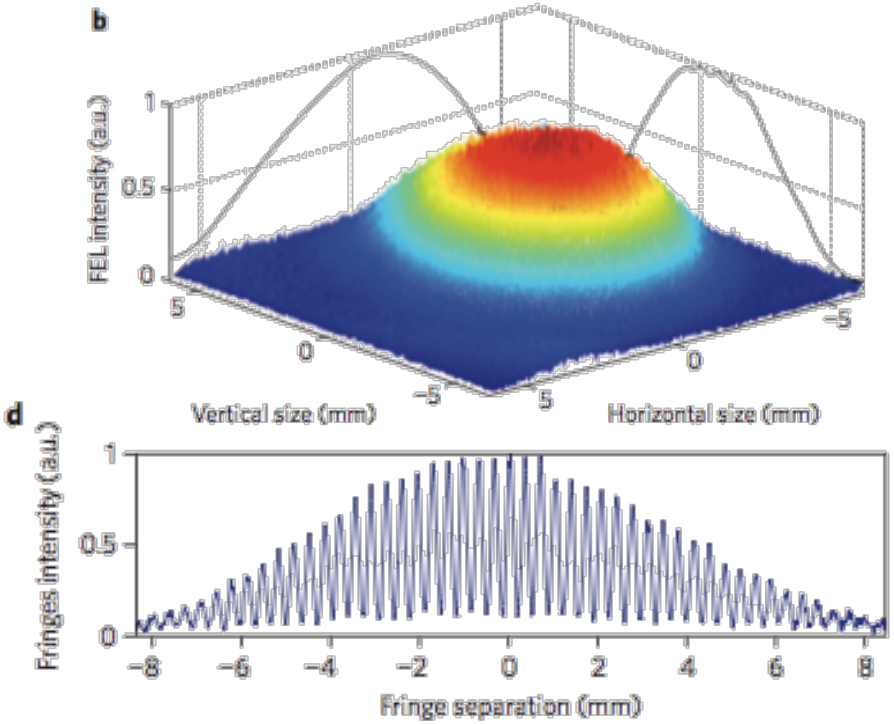
FIG. 4: Single shot HGHG spectrum for 30 MW seed (blue), single shot SASE spectrum measured by blocking the seed laser (red) and simulation the SASE spectrum after 20 m of NISUS structure (green). The average spacing between spikes in the SASE spectrum is used to estimate the pulse length.

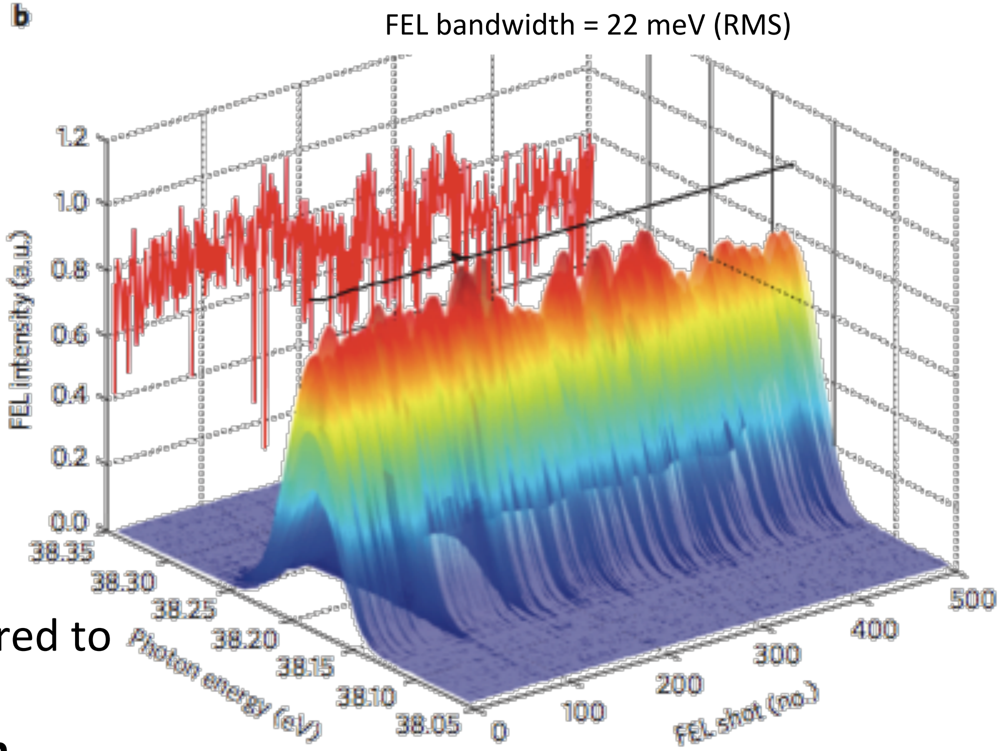


FERMI@Elettra

FERMI: Spectral stability and mode quality

In addition to the narrow spectrum FERMI pulses are characterized by excellent spectral stability. Both short and long term measurements show that the spectral peak can be stable within less than 1 part in 10^4.





FEL photon energy ~ 38.19eV
fluctuations = 1.1meV (RMS)
fluctuations = 3e-5 (RMS)

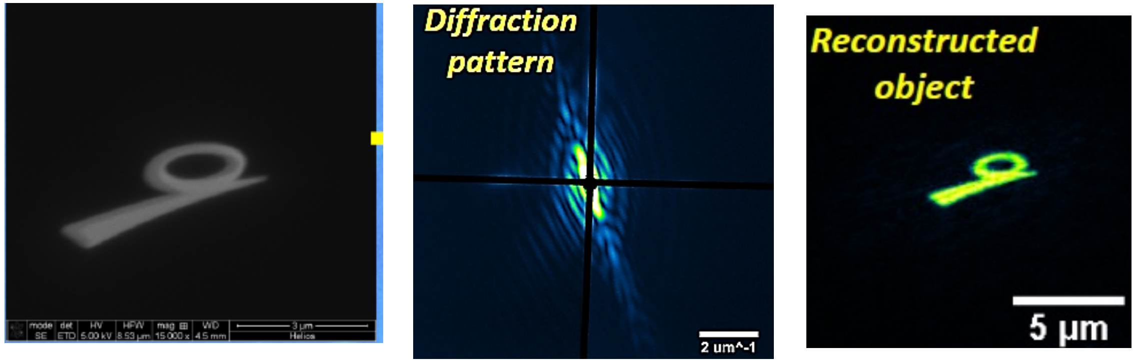
FEL bandwidth = 22 meV (RMS)

The **transverse** spatial **mode** has been measured to be very close to the **TEM$_{00}$** mode and also coherence measurements indicate a very **high degree of transverse coherence**.

"Highly coherent and stable pulses from the FERMI seeded free-electron laser in the extreme ultraviolet", E. Allaria et al., Nature Photonics 6, (2012)

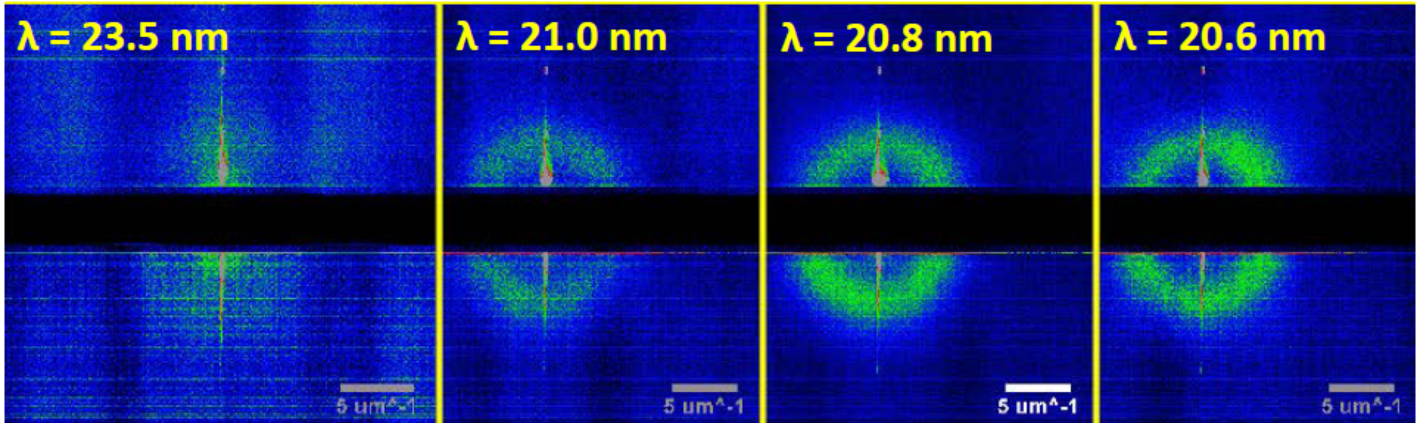
Imaging and variable polarization: DIPROI on FERMI

Single shot CDI at 32 nm



Samples, courtesy CFEL (Chapman's group)

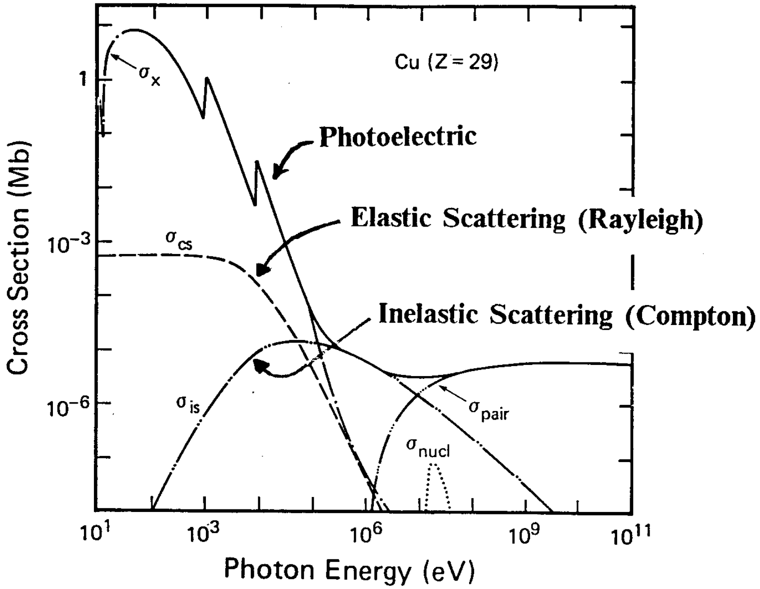
Resonant CDI at Co M edge



Sample CoPt multilayer (C. Gutt, G.Grübel et al DESY)

Photon-matter interactions

Photon interaction with electrons



Elastic Scattering

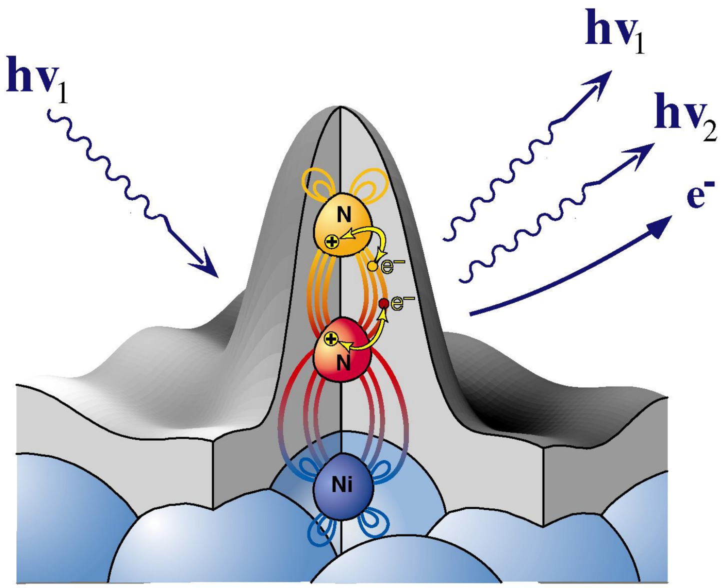
Free electron: ***Thomson Scattering***

Bound Electron: ***Rayleigh Scattering***

Inelastic Scattering

Quasi-free electron: ***Compton Scattering***

Photon Interaction with Matter



Photon-in

Absorption

Photon-in → Electron-out

Linear: ***Electron Photoemission***

Non-Linear: ***Multi-photon processes***

Photon-in → Photon-out

Elastic Scattering: ***Diffusion and Diffraction***

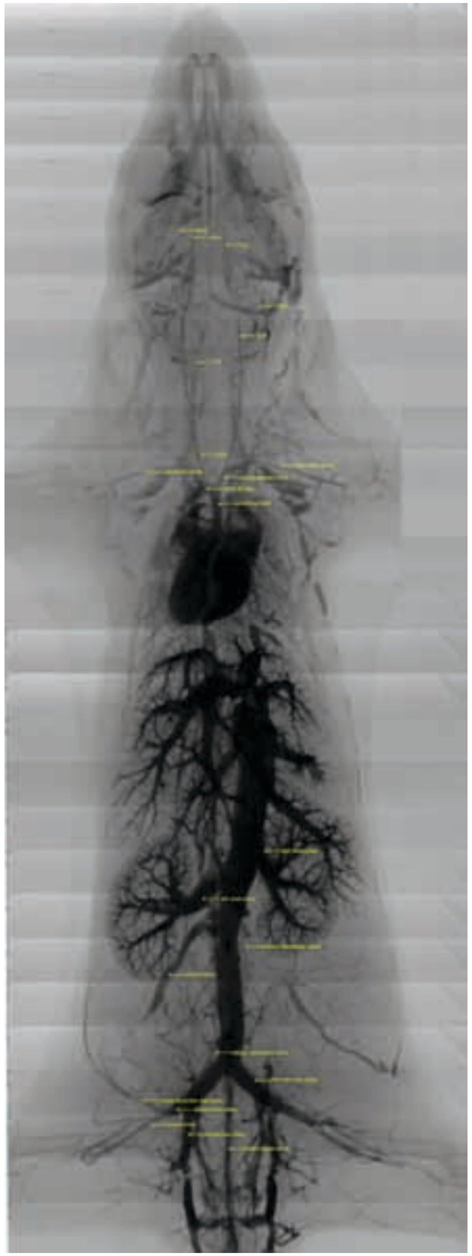
Inelastic Scattering: ***Brillouin and Raman (phononic and electronic), Fluorescence, Resonant Inelastic Scattering***

Microvascular imaging using synchrotron radiation

P. Liu, J. Sun, J. Zhao, X. Liu, X. Gu, J. Li, T. Xiao and L. X. Xu

J. Synchrotron Rad. (2010). **17**, 517–521

In vascular diseases, visualization of microvasculatures is an important step in understanding the mechanism of early vessel disorders and developing effective therapeutic strategies. However, the microvessels involved are beyond the detection limit of conventional angiography. A new angiography system, synchrotron radiation microangiography, has been developed. Iodine and barium sulfate were used as blood vessel contrast agents. Dynamic angiography in mouse brain was performed with a high spatial image resolution of 20–30 μm. Physiological features of whole-body mouse microvasculature were investigated for the first time



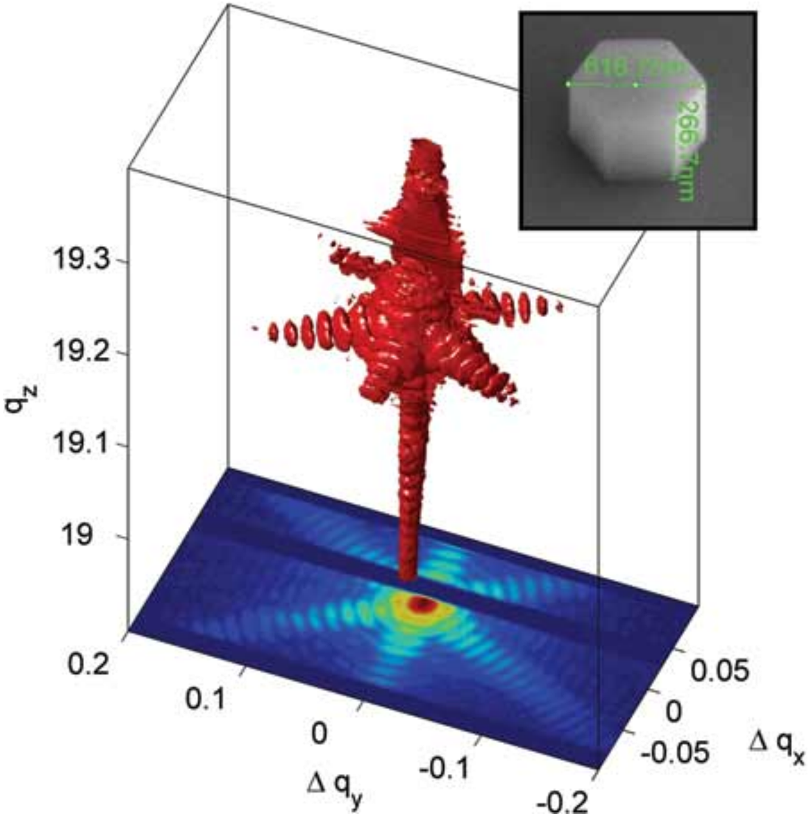
Coherent X-ray diffraction

Individual GaAs nanorods imaged by coherent X-ray diffraction

A. Biermanns, A. Davydok, H. Paetzelt, A. Diaz, V. Gottschalch, T.H. Metzger and U. Pietsch

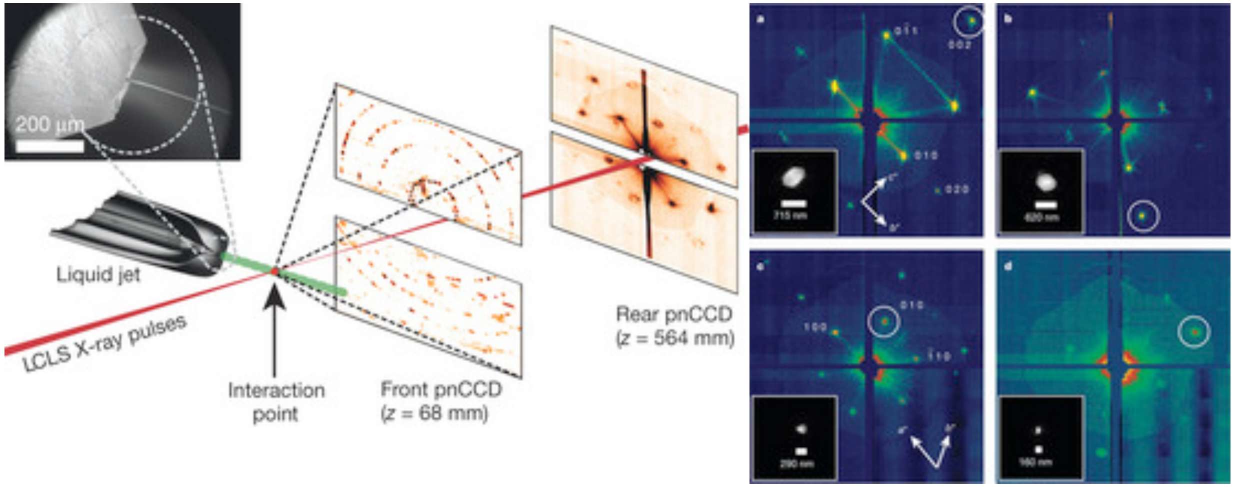
J. Synchrotron Rad. (2009). 16, 796-802

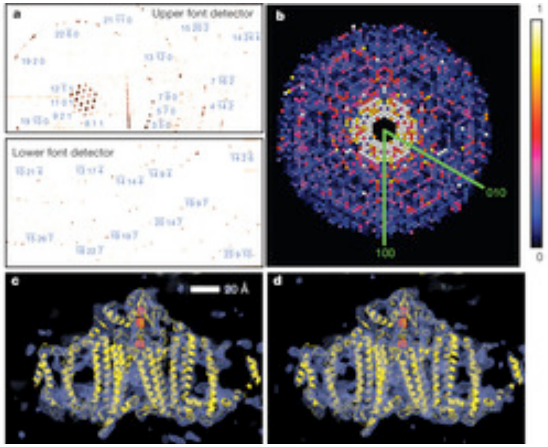
Coherent diffraction imaging in combination with a nano-focussed X-ray beam was used to identify both shape and strain state of individual hexagonally shaped GaAs nanorods within a periodic nanorod array. From the 3-dimensional intensity distribution around a Bragg peak in reciprocal space, differences in shape and strain of different nanorods could be resolved using phase-retrieval algorithms. The method is promising for the destruction-free analysis of nanoobjects.



Femtosecond X-ray protein nanocrystallography

The intense, ultrashort X-ray pulses allow diffraction imaging of small structures before radiation damage occurs. Two papers in this issue of Nature present proof-of-concept experiments showing the LCLS in action. Chapman et al. tackle structure determination from nanocrystals of macromolecules that cannot be grown in large crystals. They obtain more than three million diffraction patterns from a stream of nanocrystals of the membrane protein photosystem I, and assemble a three-dimensional data set for this protein. Seibert et al. obtain images of a non-crystalline biological sample, mimivirus, by injecting a beam of cooled mimivirus particles into the X-ray beam.





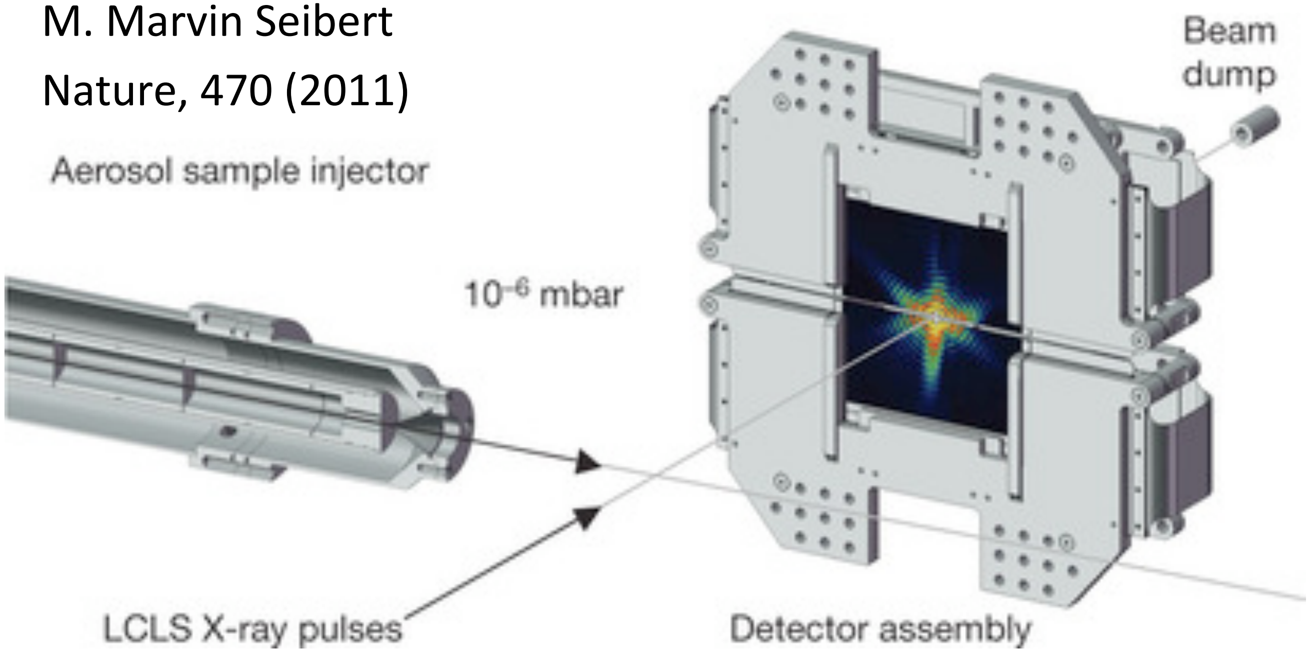
Nature, 470, 73–77 (2011)

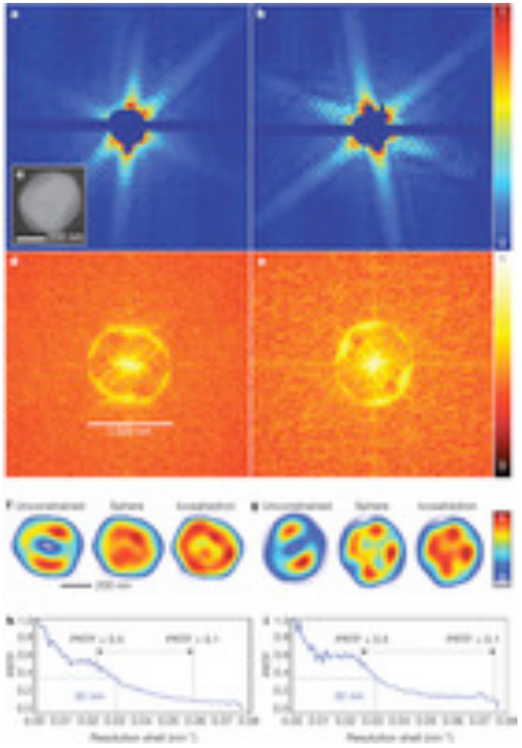
Single mimivirus particles intercepted and imaged with an X-ray laser

Very short and extremely bright, coherent X-ray pulses can be used to outrun key damage processes and obtain a single diffraction pattern from a large macromolecule, a virus or a cell before the sample explodes and turns into plasma. The continuous diffraction pattern of non-crystalline objects permits oversampling and direct phase retrieval. Here we show that high-quality diffraction data can be obtained with a single X-ray pulse from a non-crystalline biological sample, a single mimivirus particle, which was injected into the pulsed beam of a hard-X-ray free-electron laser, the Linac Coherent Light Source.

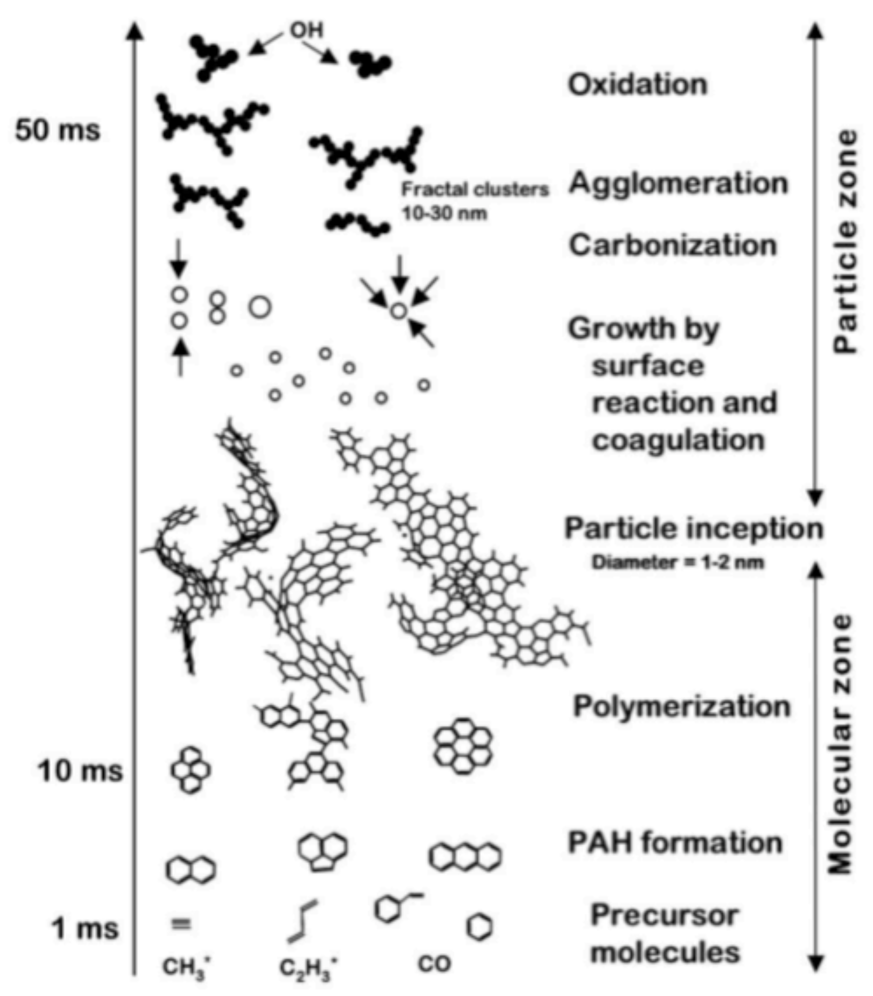
M. Marvin Seibert

Nature, 470 (2011)





Nano-particles-Coherent Imaging and Pollution



M. Bogan

Shanghai average PM2.5 = 75 ug/m^3
US EPA limit = 35 ug/m^3

7.5 million kg over 100 km^2

International Workshop on Frontiers in Synchrotron Tools
for Studies of Combustion and Energy Conversion

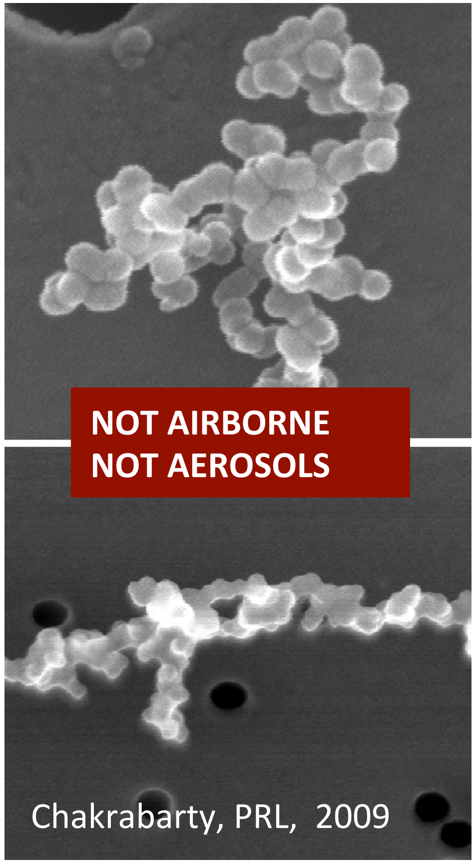
October 15 - 18, 2011 Shanghai, China

Imaging Aerosols

Ensembles

nasa.gov

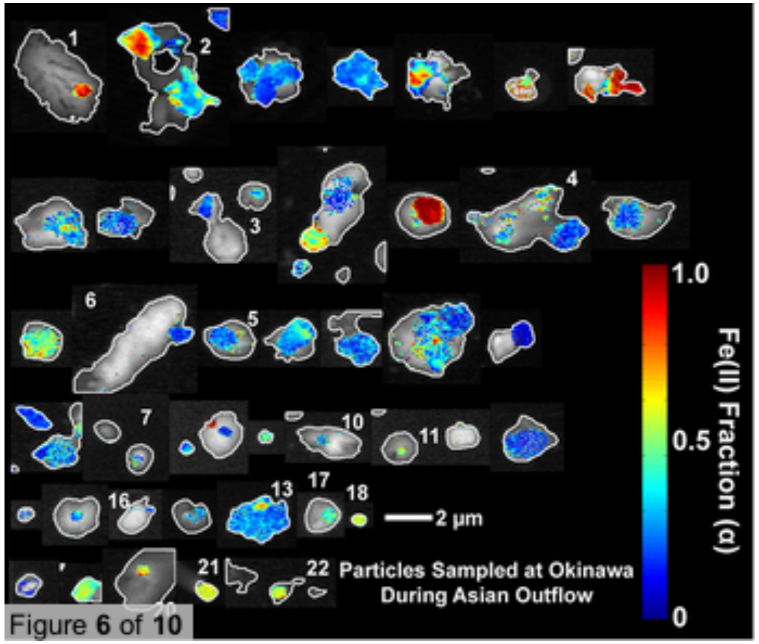
High resolution **captured** particles



NOT AIRBORNE
NOT AEROSOLS

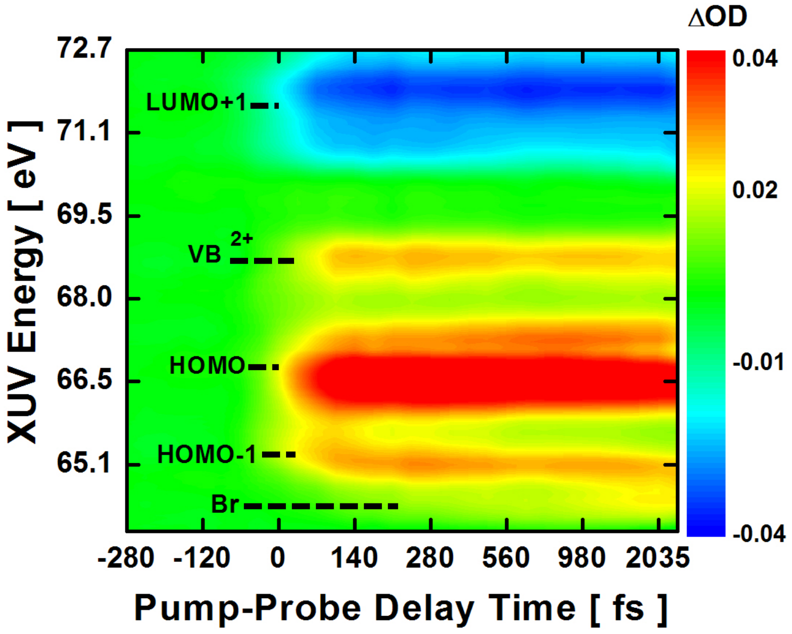
Chakrabarty, PRL, 2009

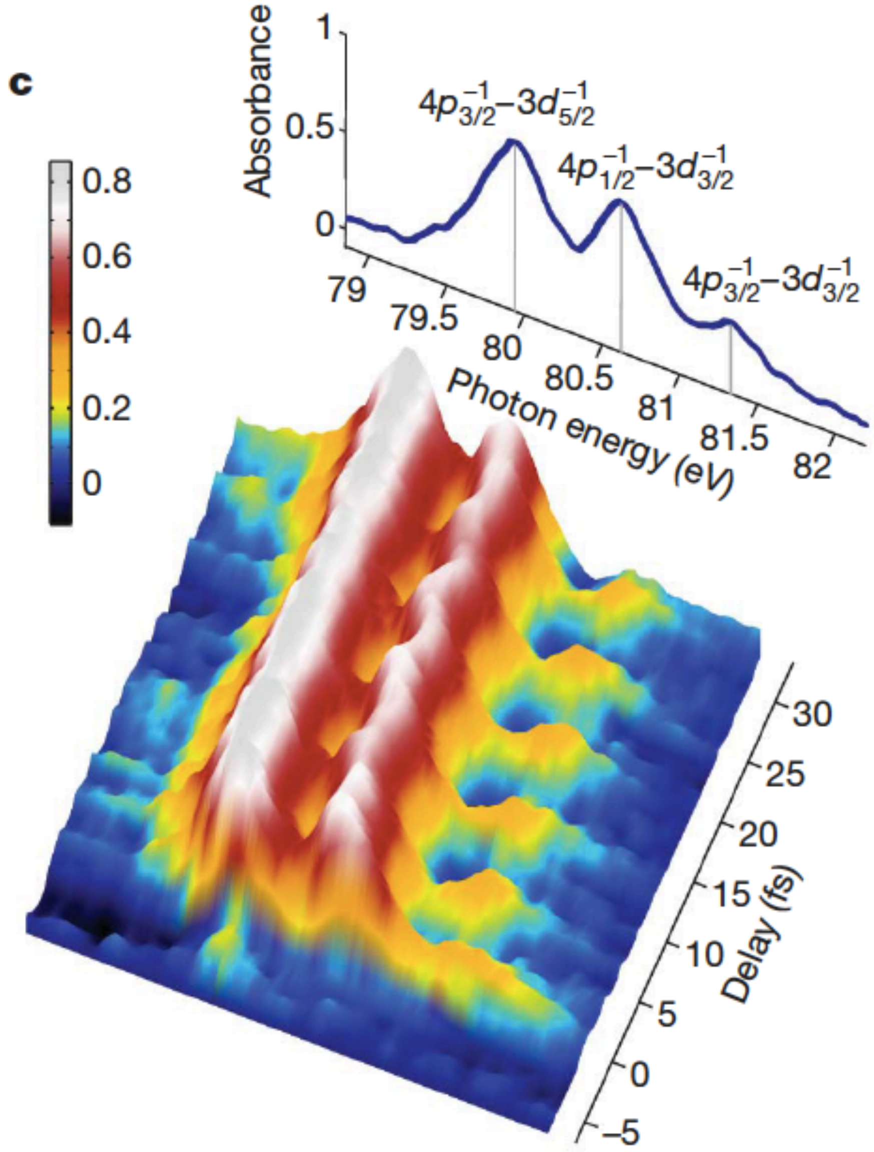
Chemical Imaging with STXM/ NEXAFS of Asian Dust Samples



Moffet, R. C., H. Furutani, T. C. Rödel, T. R. Henn, P. O. Sprau, A. Laskin, M. Uematsu, and M. K. Gilles (2012), Iron speciation and mixing in single aerosol particles from the Asian continental outflow, J. Geophys. Res., 117, D07204

Transient Absorption: The Need for Bandwidth

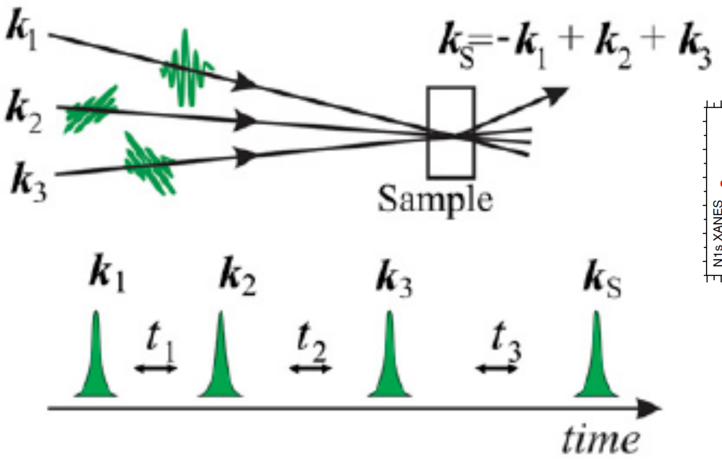


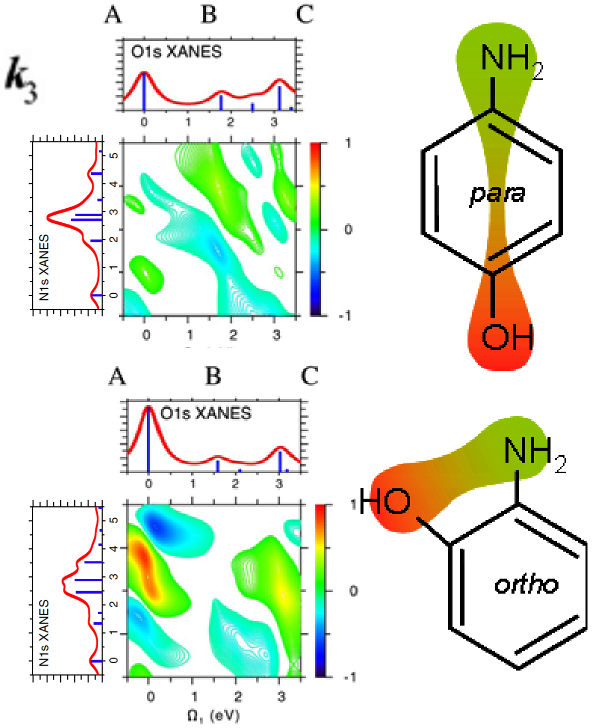


NGLS Workshop 2012

From Pump-Probe to Multidimensional X-ray Spectroscopy

multidimensional spectroscopy has revolutionized fields of science

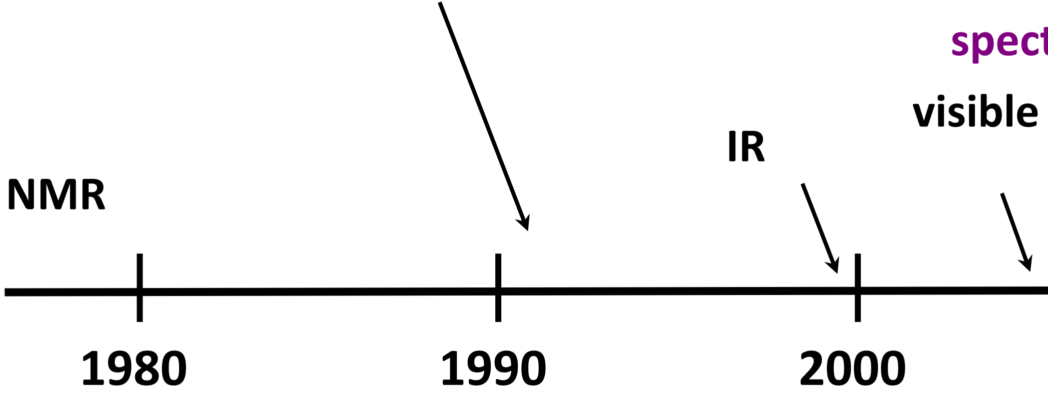




Mukamel et al, 2007

1991 Nobel Prize multidimensional NMR

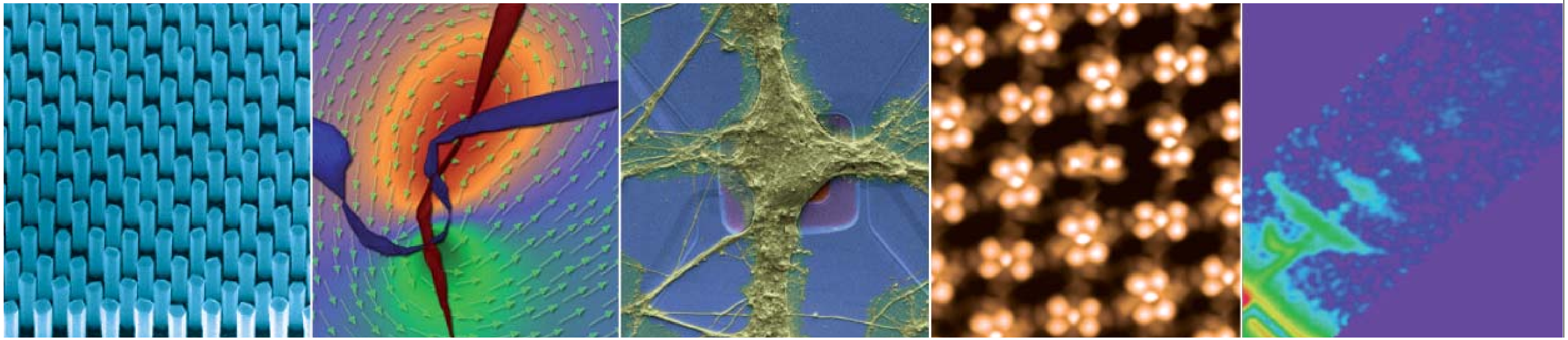
multidimensional electronic spectroscopy



NGLS Workshop 2012

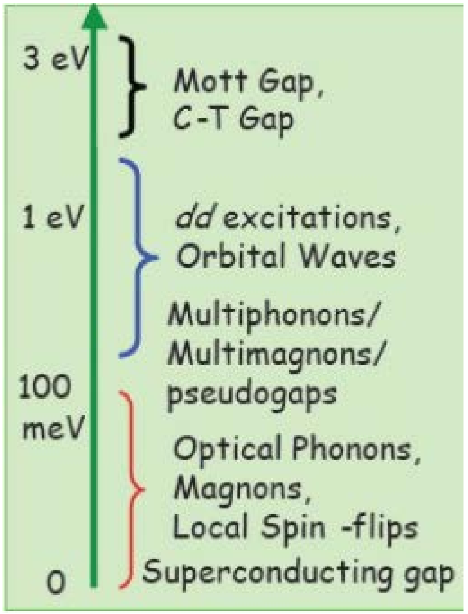
Fundamentals of Future Information Technology

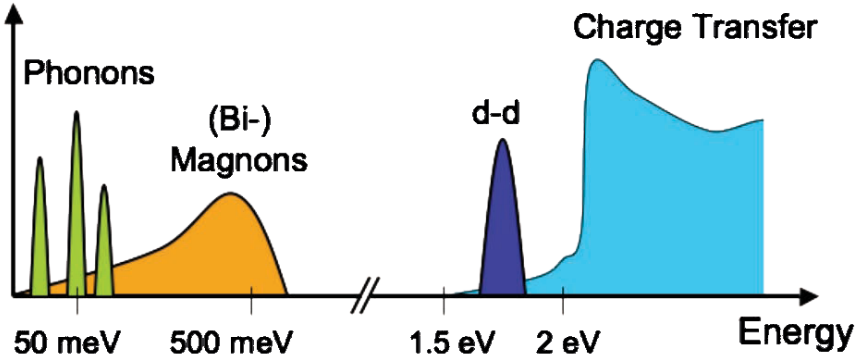
- Nanomagnetism
- Spin transport and coherence
- Magnetization switching and spin dynamics
- Nanoferronics
- Nanoionic-based non-volatile memories
- Complex surface and interface phenomena
- Exploration of novel materials



Courtesy C. M. Schneider

Elementary excitations in transition metal oxides (TMO)





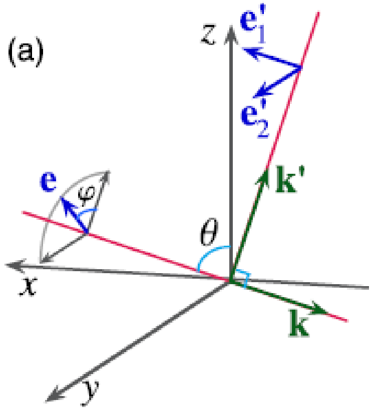
(after L.J.P. Ament et al., Rev. Mod. Phys.83 (2011) 705)

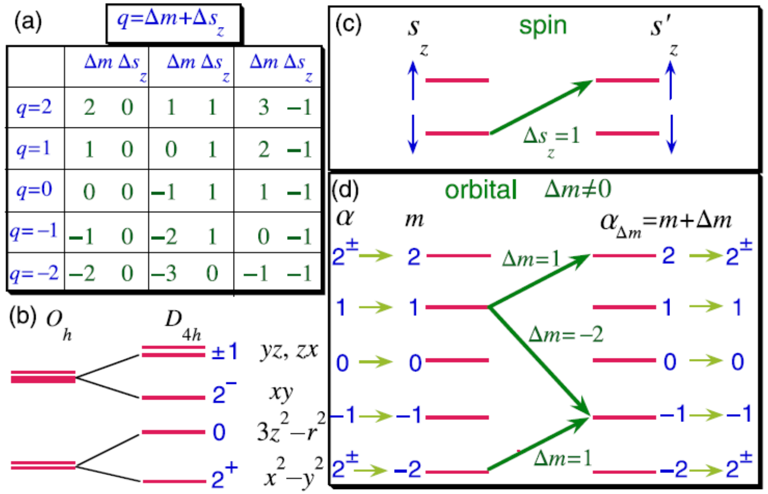
- resonant inelastic x-ray scattering from TMO's, e.g. cuprates: La_2CuO_4:
resonant excitation at Cu $M_{2,3}$-edge → probe excitation spectrum locally at Cu sites
$|0> 3p^6 3d^9 \rightarrow |i> 3p^5 3d^{10} \rightarrow |f> 3p^6 3d^{9*}$
- $3d^{9*}$ excited state: relevant electronic excitations: dd-excitation or spin-flip (magnon) or orbital excitation (orbiton)
- spin-flip allowed for certain geometries (symmetries) through spin-orbit coupling

Courtesy: W. Wurth

Polarization dependent tr-RIXS

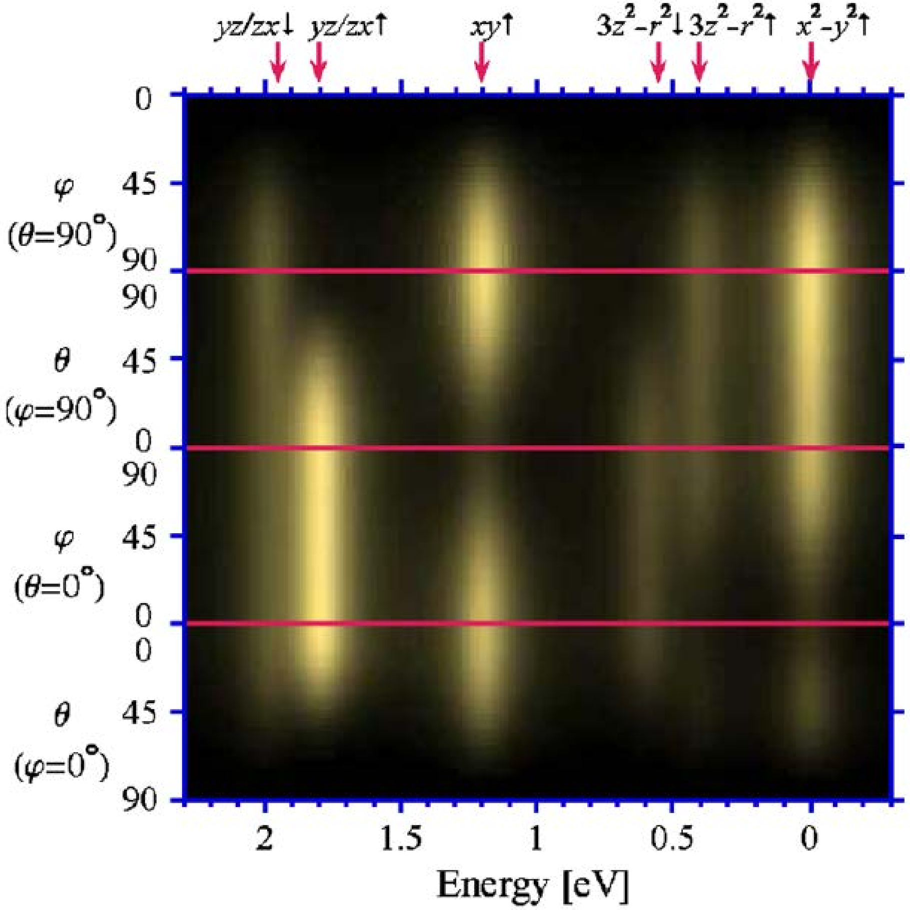
Strong polarization dependence allows identification of symmetry of excitations





(a)

$q=\Delta m+\Delta s_z$	Δm	Δs_z	Δm	Δs_z	Δm	Δs_z
$q=2$	2	0	1	1	3	−1
$q=1$	1	0	0	1	2	−1
$q=0$	0	0	−1	1	1	−1
$q=-1$	−1	0	−2	1	0	−1
$q=-2$	−2	0	−3	0	−1	−1



Polarization Dependence of L- and M-Edge Resonant Inelastic X-Ray Scattering in Transition-Metal Compounds, Michel van Veenendaal, PRL **96,** 117404 (2006)

Future Scenario

- The way to produce fully coherent X-ray radiation is paved. If also the second stage for the HGHG will be proved a new technology will be available.
- Tunability
- Variable polarization
- Full coherence
- High repetition rate

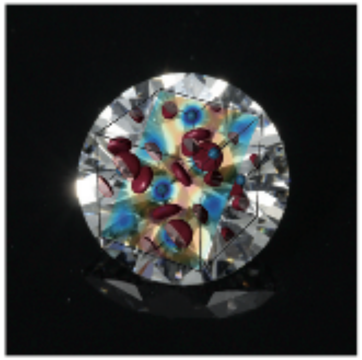
The future scenario

Coherent X-ray Optics

Quantum X-ray optics

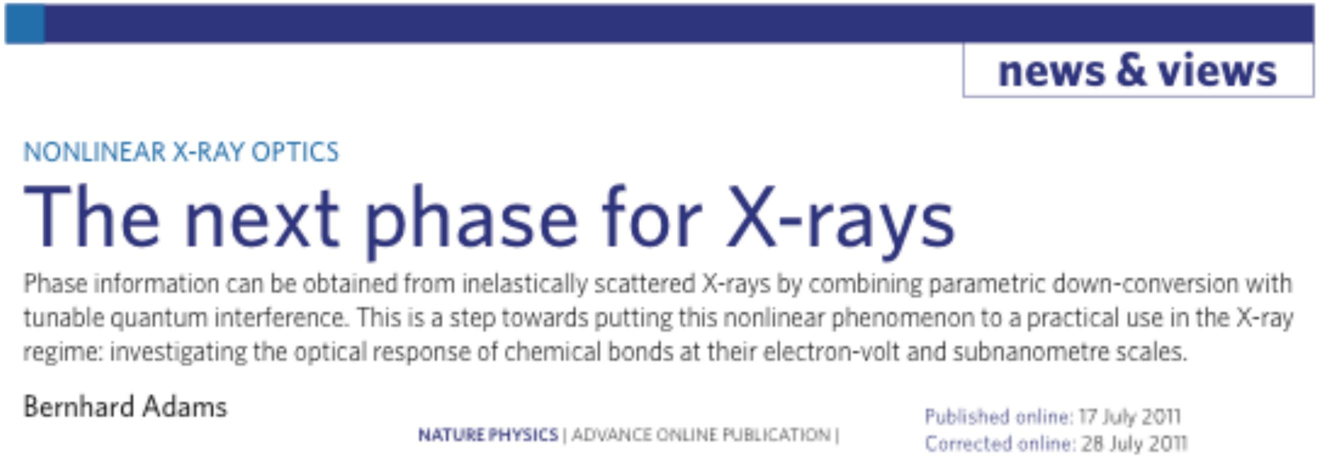
Stroboscopic phase tomography

An extraordinary effort is needed to develop a suitable science program



COURTESY OF KENJI TAMASAKU

XPDC imaging. Tamasaku *et al.*[4] use their parametric down-conversion-based technique to investigate the response of diamond to ultraviolet light at a resolution as small as 0.54 Å.



news & views

NONLINEAR X-RAY OPTICS

The next phase for X-rays

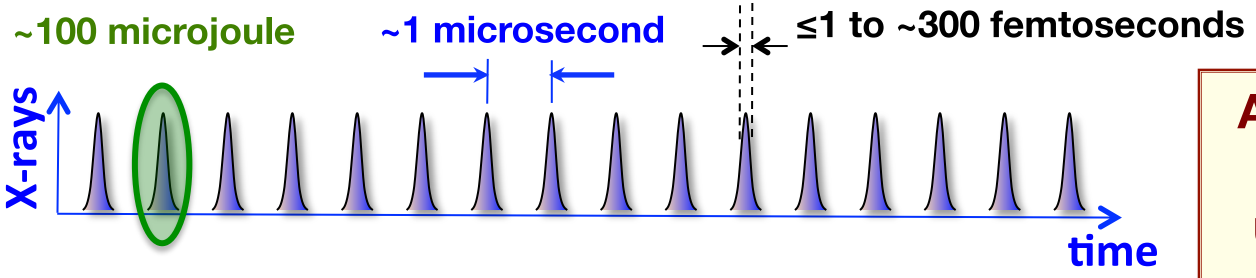
Phase information can be obtained from inelastically scattered X-rays by combining parametric down-conversion with tunable quantum interference. This is a step towards putting this nonlinear phenomenon to a practical use in the X-ray regime: investigating the optical response of chemical bonds at their electron-volt and subnanometre scales.

Bernhard Adams

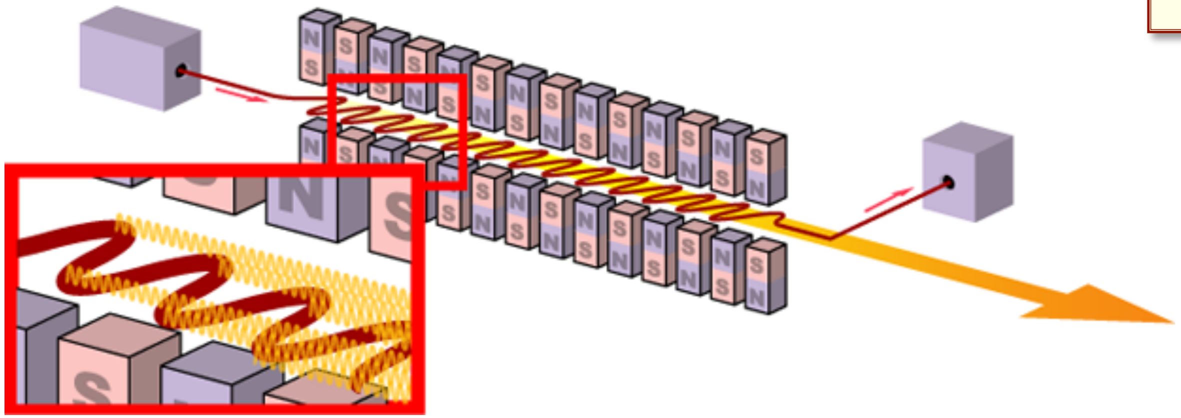
NATURE PHYSICS | ADVANCE ONLINE PUBLICATION |

Published online: 17 July 2011
Corrected online: 28 July 2011

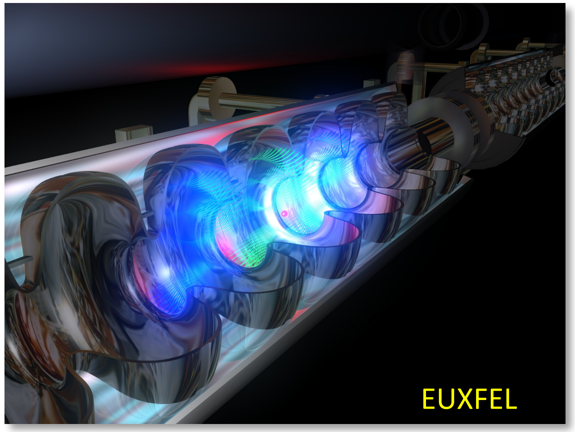
What is the NGLS?



Array of high power X-ray lasers with intense, ultrafast, coherent X-ray pulses at high rate (CW)

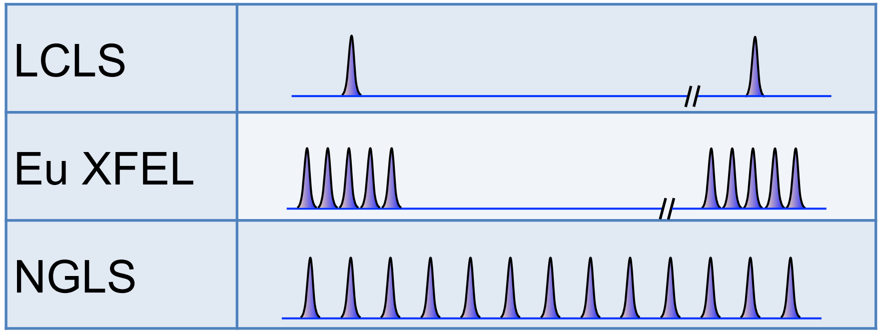


Free electron lasers (FELs) produce intense, ultrafast, coherent X-ray pulses

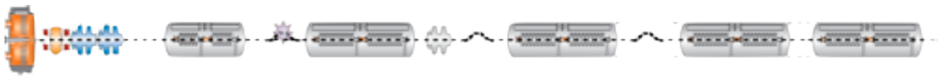


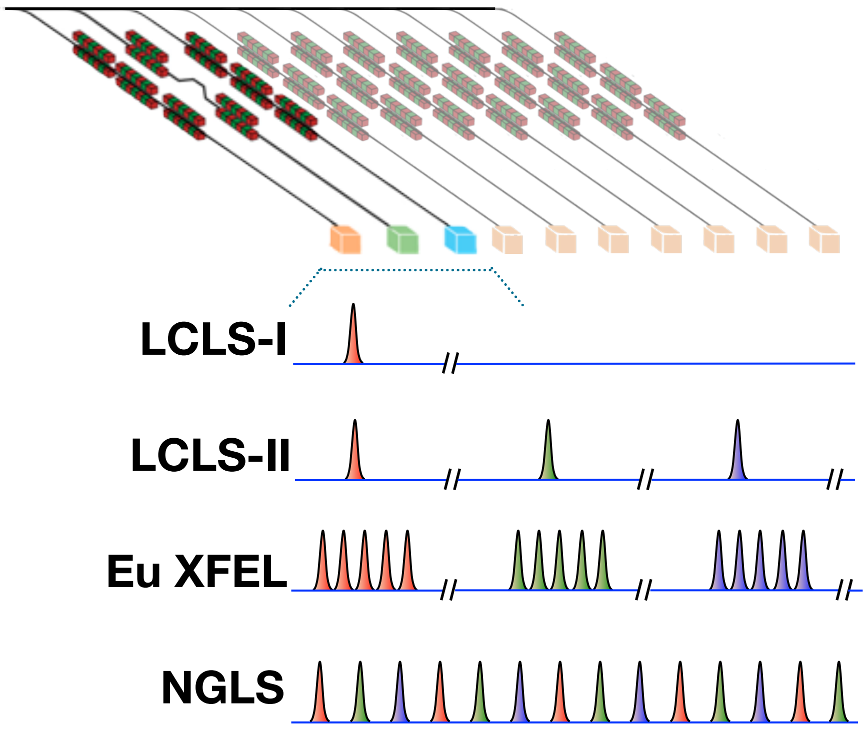
A CW superconducting linac with high-rate injector provides high-brightness electron beam

Future Scenario



NGLS





- **CW LINAC**
- **Modular FEL array**

Rep Rate **High repetition rate (≥ MHz)**

Tunability **~250 - 1,250 eV (fundamental)**

Coherence **Seeded operation**

Overview of Elettra and FERMI